Estimates of carbon stored in harvested wood products from United States Forest Service Eastern Region, 1911-2012

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Abstract

Global forests capture and store significant amounts of carbon through photosynthesis. When carbon is removed from forests through harvest, a portion of the harvested carbon is stored in wood products, often for many decades. The United States Forest Service (USFS) and other agencies are interested in accurately accounting for carbon flux associated with harvested wood products (HWP) to meet greenhouse gas monitoring commitments and climate change adaptation and mitigation objectives. National-level forest carbon accounting has been in place for over a decade, but there is an increasing need for accounting for smaller scale administrative units, including USFS National Forest System regions and individual National Forests. This paper uses the Intergovernmental Panel on Climate Change (IPCC) production accounting approach to estimate HWP carbon storage from 1911 to 2012 for the USFS Eastern Region. For the Eastern Region as a whole, carbon stocks in the HWP pool were increasing steadily from 100,000 megagrams of carbon (MgC) per year in the early 1950s up to 416,000 MgC in 1987, with peak cumulative storage to date of slightly less than 12.7 million MgC occurring in 2013. Net positive flux into the HWP pool over this period is primarily attributable to high harvest levels in the 1980s and 1990s. Harvest levels have declined since the 1990s and have been erratic since the year 2000, yet carbon entering the HWP pool continues to increase. The Eastern Region HWP pool has always been in a state of positive net annual stock change because additions of carbon to the HWP pool through harvest exceeds the decay of products harvested between 1911 and 2012. Together with estimates of ecosystem carbon, which are also being developed through the Forest Management Carbon Framework (ForCaMF), Regional level estimates of HWP carbon flux can be used to inform management decisions and guide climate change adaptation and mitigation efforts by the agency. Though our emphasis is on the Eastern Region as a whole, this accounting method can be applied more broadly at smaller land management units, such as National Forests.

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Cover: Red pine salvage operation in a blow down stand on the Chippewa National Forest in north central Minnesota. Photo courtesy of Mary Nordeen (Chippewa National Forest, Cass Lake, MN).

Contents

Background

Recent estimates of net annual storage (flux) indicate that the world's forests are an important carbon sink, removing more carbon dioxide (CO_2) from the atmosphere through photosynthesis than they emit through combustion and decay (Pan et al. 2011). The forest sector of the United States (US) currently stores about 45 billion megagrams of carbon (MgC), or the equivalent of about 24 years of total US emissions at the 2010 rate (US EPA 2012). Nationally, net additions to ecosystem and harvested wood products (HWP) pools have been estimated at 251.4 million MgC yr^{-1} (US EPA 2012), with US forests offsetting about 13.5% of the country's annual fossil fuel emissions. About 5.5% of total US forest sector carbon stocks and 7.1% of the annual flux is attributable to carbon in HWP. Increasing social and managerial interest in mitigating rising atmospheric CO_2 concentrations and the resulting impacts on climate has focused attention on the ecosystem service of forest carbon storage, including storage in HWP.

As defined by the Intergovernmental Panel on Climate Change (IPCC), HWP are products made from wood including lumber, panels, paper, paperboard, and wood used for fuel (Skog 2008). The HWP carbon pool includes both products in use and products that have been discarded to solid waste disposal sites (SWDS). Additions to the HWP pool are made through harvesting, and emissions result from decay and combustion of wood products. Forest management can affect the quantity of carbon stored in both ecosystems and forest products over time, and management activities in the US frequently include silvicultural treatments that produce HWP. Credible information on forest ecosystem and HWP carbon stocks and fluxes can inform forest managers and the public of the tradeoffs between carbon storage and other forest management objectives, and between the short and long-term carbon consequences of alternative forest management strategies (Ryan et al. 2010, McKinley et al. 2011, Galik and Jackson 2009). Though the HWP fraction of the pool is small compared to ecosystem carbon, it is an important component of national level carbon accounting and reporting.

There is growing interest among forest managers in monitoring and managing forests for sequestration of carbon as an ecosystem service. For example, during 2010, the US Forest Service (USFS) developed a climate change scorecard that will be completed annually for each of the 155 National Forests and grasslands managed by the agency (USFS 2011). The scorecard includes four categories of scored elements: organizational capacity, engagement, adaptation, and mitigation and sustainable consumption. Elements under mitigation and sustainable consumption direct individual National Forests to develop a baseline assessment of carbon stocks, as well as an assessment of the influence of disturbance and management activities on these stocks. These assessments are meant to guide mitigation actions and monitoring. Managers are expected to begin integrating carbon stewardship with management of their forest for traditional multiple uses and other ecosystem services (USFS 2011). Consequently, these requirements necessitate robust and accessible monitoring systems that provide quantitative metrics to gauge progress.

HWP carbon monitoring systems have been implemented at the national level (US EPA 2012, Skog 2008, IPCC 2006, Smith et al. 2006). Robust inventory-based methods for estimating carbon stocks and flux in forest ecosystems are well established in the US and several tools are available to forest managers (Smith et al. 2006, 2004, Zheng et al. 2010, Galik et al. 2009). However, many of the tools used to estimate carbon stored in forests do not provide estimates of HWP carbon (e.g., U.S. Forest Carbon Calculation Tool, Smith et al. 2007) while others are restricted to national level HWP accounting (e.g., WOODCARB II, Skog 2008). Neither model independently serves National Forest managers who need accessible and practical tools for estimating and monitoring carbon stocks and flux in HWP, which were harvested since the inception of their units, at the regional or National Forest levels (Ingerson 2011, Stockmann et al. 2012).

Objectives

There is a clear need to develop the means to monitor the contribution of HWP to carbon pools and greenhouse gas mitigation resulting from National Forest harvests both at the regional and forest levels. Our objectives are to:

1) Use an established accounting approach to make estimates of HWP carbon stocks and fluxes for the USFS Eastern Region;
2) Provide a framework with clear metrics and estimation methods that can be applied to other land management units, including individual National Forests.

We do not develop a system for evaluating the future impacts of specific management actions, nor do we advocate any particular course of action to improve carbon stewardship.

Regional Description

The US Forest Service Eastern Region currently administers approximately 12.1 million acres of National Forest fragmented across 20 Great Lakes and northeastern States, containing 41% of the nation's population, and representing approximately 6% of total US National Forest System lands. Of the total acreage, 11.2 million acres are timbered, 1.5 million acres are reserved (i.e. wilderness, Research Natural Areas), and approximately 6.9 million acres are suitable for timber production. Dominant forest types are oak/hickory, maple/beech/birch, spruce/fir, elm/ash/cottonwood, and white/red/jack pine. The Eastern Region includes the Allegheny, Chequamegon-Nicolet, Chippewa, Green Mountain and Finger Lakes, Hiawatha, Hoosier, Huron-Manistee, Mark Twain, Monongahela, Ottawa, Shawnee, Superior, Wayne, and White Mountain National Forests.

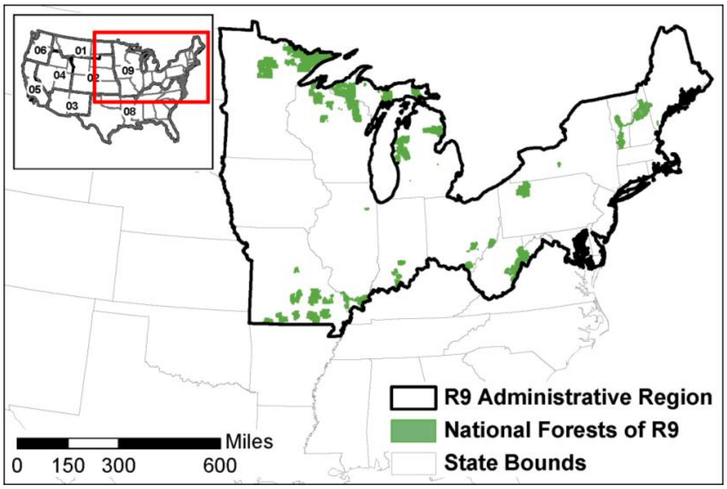

Figure 1. Map of the Eastern Region (also known as R9).

Historical Eastern Region land base changes

Forestland included in many Forest Service Regions has changed over time. In cases where administrative boundaries between Regions have changed, we used forest-specific data to standardize Regional harvest totals. The Eastern Region boundary changed in 1965 from its former land base to include National Forests in the northeastern States east of Ohio and north of Virginia, all previously administered by Region 7. Estimates of Eastern Region HWP carbon include timber harvested from National Forest land within the Region's current administrative boundary from 1911 to 2012, including timber harvested from the former Region 7 National Forests in the northeast. Where these changes occurred, inclusion or exclusion of harvest volumes in this report were supported by details in national level reports. Administrative boundary changes among National Forests within the Region do not affect the estimates presented here and would only be relevant to produce HWP carbon stocks and flux estimates for individual National Forests.

Methods

The method used to estimate carbon stored in HWP for the Eastern Region is discussed here in four parts: accounting approach, computational methods, data sources, and uncertainty analysis. The first part provides a general overview of the framework used for carbon accounting, including defining the scope of analysis, relevant carbon pools, and associated fluxes. The second part provides detailed information about the data we used in our calculations that transform harvest data into carbon accounting metrics. Then we describe the origins of the data used in this analysis, with an emphasis on understanding what inputs are required and how data quality can vary over time. Lastly, the quantitative treatment of uncertainty is discussed in light of limitations of the approach used, computational methods, and data.

Accounting Approach

We use the IPCC production accounting approach, which has been adopted by the US Environmental Protection Agency (EPA; hereafter referred to as the IPCC/EPA approach) to estimate annual changes in HWP pools from the Region (Figure 2). In the IPCC/EPA approach, the annual carbon stock change for the Region's forest sector is a function of carbon flow among the atmosphere, forest ecosystems, and HWP, and is calculated as:

$$\Delta S = (NEE - H) + (\Delta C_R)$$

In this equation ΔS is the annual stock change for the Region's forest sector, NEE is the annual net ecosystem exchange between the atmosphere and the Region's forests from all ecosystem processes including photosynthesis, decay, and natural and anthropogenic fire, H is the annual harvest of wood from the Region's forests for products, and ΔC_R is the annual change in carbon stored in HWP that were made from wood harvested from the Region's National Forests (Table 1, Figure2). In the IPCC/EPA approach, the annual change in carbon stored in HWP (ΔC_R) is the sum of the net change in carbon stored in products in use ($\Delta C_{IU\ R}$) and the net change in carbon stored in products at solid waste disposal sites ($\Delta C_{SWDS\ R}$) (Table 1). By estimating stocks and emissions for regional HWP carbon on an annual basis, we can calculate the annual stock change in the HWP carbon pool (ΔC_R), which is the relevant metric for this accounting approach. HWP carbon stock and flux estimates presented here are part of a larger Forest Carbon Management Framework (ForCaMF) intended to address carbon storage in the entire forest system (ΔS).

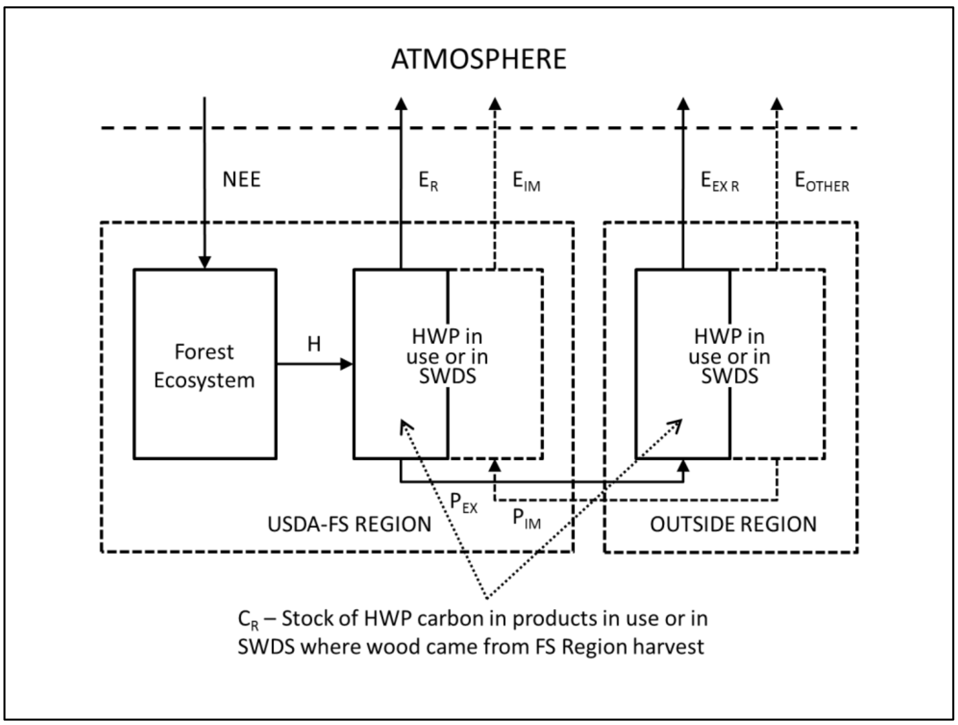

Figure 2. Carbon flows and stocks associated with forest ecosystems and harvested wood products (HWP) to illustrate the IPCC/EPA production accounting approach (adapted from Skog 2008).

Table 1. Variable definitions for the IPCC/EPA production accounting approach shown in Figure 2 (Skog 2008). Units for all variables are MgC yr^{-1}.

Variable	Definition
ΔS	Annual carbon stock change, which is calculated as $\Delta S=(NEE-H)+(\Delta C_{R1})$ in the production accounting approach.
NEE	Annual net ecosystem carbon exchange, the annual net carbon that moves from the atmosphere to forests.
H	Annual harvest of wood for products, which includes wood and residues removed from harvest sites, but excludes resides left at harvest sites.
HWP	Harvested wood products in use or at solid waste disposal sites.
E_R	Annual emission of carbon to the atmosphere in the Region from products made from wood harvested in the Region.
E_{IM}	Annual emission of carbon to the atmosphere in the Region from products made from wood harvested outside of the Region and imported into the Region.
P_{EX}	Annual exports of wood and paper products out of the Region, including roundwood, chips, residue, pulp and recovered (recycled) products.
P_{IM}	Annual imports of wood and paper products into the Region, including roundwood, chips, residue, pulp and recovered (recycled) products.
$E_{EX\ R}$	Annual emission of carbon to the atmosphere in areas outside of the Region from products made from wood harvested in the Region.
E_{OTHER}	Annual emission of carbon to the atmosphere in areas outside of the Region from products made from wood harvested outside the Region.
C_R	Stock of harvested wood products carbon in use or at solid waste disposal sites where products used wood from the Region.
$\Delta C_{IU\ R}$	Annual change in carbon stored in harvested wood products in use where products used wood from the Region.
$\Delta C_{SWDS\ R}$	Annual change in carbon stored in harvested wood products at solid waste disposal sites where products used wood from the Region.
ΔC_R	Annual change in carbon stored in harvested wood products in use and at solid waste disposal sites where products used wood from the Region.

System boundaries

Most people are familiar with imports and exports in the context of international trade, but the concept can be applied to understand the treatment of carbon imports and exports in the IPCC/EPA approach. In this case the terms export and import refer to the border of the Eastern Region. For example, HWP manufactured in a USFS Region may be used locally by consumers inside the Region or exported from the local area for use elsewhere. Similarly, HWP produced outside the Region may be imported for use within the Region. Figure 2 shows that carbon emissions attributed to HWP from the Region (indicated with solid boxes) include both emissions to the atmosphere from wood products harvested and used within the Region (E_R) and emissions to the atmosphere from wood products harvested in the Region that were exported outside the Region ($E_{EX\ R}$). Emissions (E_R and $E_{EX\ R}$) are further categorized as emitted with energy capture (e.g. fuelwood) and emitted without energy capture (e.g. decomposition and burning for waste disposal). Exports (P_{EX}) include wood and paper products, as well as roundwood, chips, residue, pulp and recovered (recycled) products from wood harvested in the Region. Under the IPCC/EPA approach, imports from elsewhere (indicated with dotted lines around the right side of both HWP boxes) are not included in regional accounting because the emphasis is on the location of harvest (H).

Additionally, this approach does not account for all emissions associated with HWP. For example, carbon emissions from fossil fuels used in harvest, transportation and manufacture of HWP are not deducted from the HWP pool. Similarly, although HWP emissions with energy capture are quantified in the IPCC/EPA approach, they are not assumed to substitute for an equivalent amount of fossil fuel carbon, potentially reducing fossil fuel emissions in some scenarios (Jones et al. 2010). Furthermore, this approach does not incorporate carbon fluxes associated with product substitution, such as the substitution of HWP for metal or concrete (or vice versa) in building applications, and the associated land use changes that may ensue.

Though these types of emissions tradeoffs are outside the scope and purpose of the approach applied in this report, there are well-developed methods of life cycle assessment (LCA) that account for all carbon emissions associated with manufactured products and that facilitate the comparison between wood products and alternative products (Rebitzer et al. 2004). The IPCC/EPA approach provides information that can be used in an LCA, but in general an LCA is used to address different questions.

If management decisions require information about harvesting, transportation and processing emissions, product substitutions, or other trade components not included in the approach used here, a consequential LCA is appropriate. However, for sub-national carbon accounting, the IPCC/EPA approach has several benefits over LCA. It is relatively easy to apply and congruent with US national carbon accounting standards, which is particularly important in developing tools that can be used by USFS managers to meet carbon monitoring goals.

Computational Methods

Figure 3 provides a flow chart of the computational methods used to calculate annual stock changes and emissions from HWP for the IPCC/EPA production accounting approach. This approach does not apply simple storage ratios to the harvest; rather it tracks carbon through the product life cycle from harvest to timber products to primary wood products to end use to disposal, applying best estimates for product ratios and half-lives at each stage.

When possible, harvest records are used to distribute annual cut volumes among specific timber product classes (e.g., softwood ties, softwood sawlogs, softwood pulpwood, softwood poles, softwood fuel wood, softwood non-saw, etc.). For periods of time when timber product classes were not recorded, ratios available from a more recent time period were used. Timber products are further distributed to specific primary wood products (e.g. softwood lumber, softwood plywood, softwood mill residue used for non-structural panels, etc.) using default average primary product ratios from national level accounting that describe primary products output according to regional forest industry structure (Smith et al. 2006, Appendix A). Mill residues are included as primary wood products with some entering solid waste disposal immediately and some getting converted into products that rely on mill residues as raw material, such as particleboard and paper. The timber product to primary wood product ratios vary by region and in most cases the geography of the regions used in national level accounting does not match perfectly the boundaries of Forest Service administrative regions. Therefore, applying default ratios for part or all of the accounting time period requires some judgment in selecting the appropriate ratios, and the ratios for national regions are sometimes modified. Primary wood product outputs are converted from their reporting units to MgC using standard conversion factors for primary wood products (Smith et al. 2006, Table 2). The ratios from Smith et al. (2006) are applied to the entire time period, but are adjusted with consideration of the timing of manufacturing capacity in each region.

The recalcitrance of carbon in HWP is highly dependent on the end use of those products. For example, carbon in lumber used in new single family home construction has a longer duration than carbon in lumber used for shipping containers, which is released into the atmosphere more quickly through combustion and decay. For years 1950 through 2012, annual primary wood product output was distributed to specific end uses according to annual wood product consumption estimates in McKeever (2009, 2011).

Table 2. Conversion factors used in this analysis.

Conversion	Units
1.6303	ccf per mbf, timber harvest prior to 2000[1]
33 to 42	lbs per cubic foot, primary products
2204.6	lbs per Mg
0.95 to 1.0	Mg wood fiber per Mg product
0.5	Mg carbon per dry Mg wood fiber
0.711 to 0.919	MgC per ccf, primary products

For each of the 203 different possible end uses from the Region's HWP (e.g., softwood lumber/new housing/single family, softwood lumber/new housing/multifamily, softwood lumber/new housing/manufactured housing, softwood lumber/manufacturing/furniture, softwood lumber/packaging and shipping, etc.) for each vintage year, the amount of carbon remaining in use at each inventory year is calculated based on the product half-life and the number of years that have passed between the year of harvest and the inventory year. The half-life value expresses the decay rate at which carbon in the products in use category passes into the discarded category, representing the transition between the two pools. The carbon remaining in HWP in use in a given inventory year is calculated for each vintage year end use based on a standard decay formula:

$$N_t = N_0 \exp(-t\ln(2)/t_{1/2})$$

where N_t is the amount of carbon remaining in use in inventory year t, N_0 is the amount of carbon in the end use category in the vintage year of harvest, t is the number of years since harvest, $t_{1/2}$ is the half-life of carbon in that end use, and exp is notation for the exponential function. In our calculations, the starting amount (N_0, at n=0) is adjusted downward by 8% to reflect a loss when placed in use, which is assumed to enter the discarded carbon category. This loss in use accounts for waste when primary products (e.g. softwood lumber) are put into specific end uses (e.g. new single family residential housing), and this waste is immediately distributed to the discarded products category. Fuelwood products are assumed to have full emissions with energy capture in the year they were produced.

For carbon of a particular vintage in a given inventory year, the balance of carbon in HWP that is not in use and not emitted with energy capture is assumed to be in the discarded products category (Figure 3). Carbon in the discarded products category is partitioned into five disposition categories: burned, recovered, composted, landfills and dumps. The proportion of discarded products that ends up in each of these five categories is different for paper and solid wood products, and has changed over time. For example, prior to 1970 wood and paper waste was generally discarded to dumps, where it was subject to higher rates of decay than in modern landfills. Since then, the proportion of discarded wood going to dumps has dropped to below 2%, while the proportion going to landfills has risen to 67%, with the remainder going to the other disposition categories (Skog 2008). Similarly, composting and recovery (i.e. recycling and reuse) have become a more prominent part of waste management systems. In 2004, approximately 50% of paper waste was recovered, compared to 17% in 1960. The disposition of carbon in paper and solid wood products to these categories is based on percentages in Skog (2008).

Carbon from burned and composted discarded products is assumed to be emitted without energy capture. Carbon in the recovered category reenters the products in use category in the year of recovery. Carbon in products discarded to landfills and dumps are subject to decay determined by their respective half-lives. The half-life value for discarded products in dumps and landfills expresses the decay rates at which carbon in these categories is emitted to the atmosphere. However, our calculations consider the fact that only a fraction of the discarded products pool in landfills is considered to be subject to decay; 77% of solid wood carbon and 44% of paper carbon in landfills is identified as fixed carbon, not subject to decay (Skog 2008). For a given vintage year, the carbon remaining in SWDS in a given inventory year is the sum of fixed carbon and the carbon remaining after decay. We do not account for the difference between methane and CO_2 emissions from landfills in terms of CO_2 equivalents, nor do we account for methane remediation that includes combustion and subsequent emissions with energy capture. All landfill and dump emissions are considered emissions without energy capture.

[1] Both mbf and ccf are available in all timber harvest reports after 2000.

These methods were used to calculate annual gross stocks and gross emissions for all inventory years 1911 through 2012. Results for each inventory year were used to calculate net change in stocks of carbon in regional HWP products in use ($\Delta C_{IU\ R}$) and SWDS ($\Delta C_{SWDS\ R}$), as well as net change in emissions from SWDS and fuelwood (E_R).

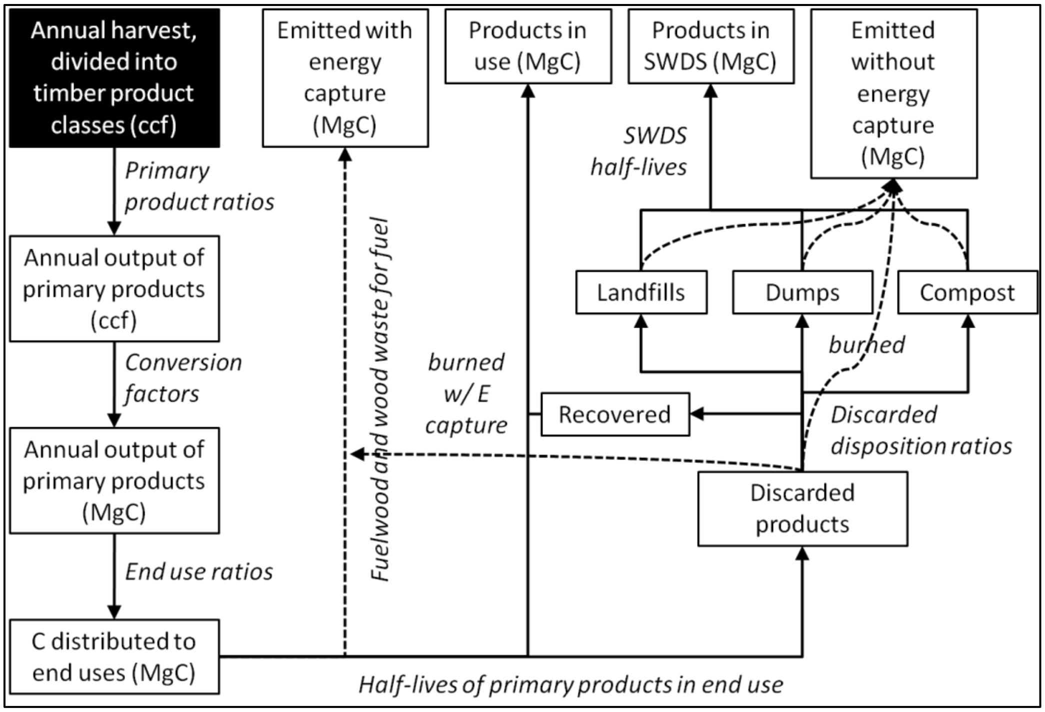

Figure 3. A schematic of calculations to quantify HWP storage and emissions. These calculations quantify HWP products in use, products in SWDS, emissions with energy capture, and emissions without energy capture using the IPCC/EPA approach.

Online Harvested Wood Products Carbon Accounting Tool

Calculations were facilitated by an online HWP carbon accounting tool developed by USFS and cooperators (USURS 2012). The tool requires two inputs: a harvest time series and a time series of timber product ratios that partition the harvest into different timber product classes, which are discussed in the following section. In addition, the user can enter primary product ratios if they are known, or use the default values from Smith et al. (2006). The option to input primary products ratios allows the user to more accurately reflect regional changes in industry structure and associated primary product manufacturing if desired. The user can also provide additional inputs to guide the Monte Carlo simulations that determine statistical confidence intervals, including random variable distributions and number of iterations, or use the default values provided. The latest version of the tool, with supporting documentation, can be found at: http://maps.gis.usu.edu/HWP.

Data Sources

Data quality impacts the uncertainty and reliability of our estimates, and the data used in this analysis provide a good illustration of the challenges associated with using historical data in carbon accounting. This section is divided into four parts: first we discuss historical timber harvest data acquisition and limitations, and how those limitations were addressed. Following that we describe how the data were allocated to timber products, how timber products were allocated to primary products and finally how we allocate primary products to end use products for all Regions. By standardizing boundaries and units and partitioning the harvest among different timber and primary product classes, we created a continuous dataset spanning 1911 through 2012 that meets the criteria for estimation established by the IPCC (2006).

Historical timber harvest data

Regional harvests have been reported in detailed cut-and-sold reports and are available online from 1977 to the present[2]. These reports include the value and volume of timber sold and harvested in the Region, which are reported by both fiscal and calendar year. In addition, total harvests are partitioned by sale value, timber product class[3], tree species, and National Forest within the Region. Records for annual harvest prior to 1977 are generally more difficult to obtain; for the Eastern Region, consistent harvest data from 1911 through 1965 were not available at the Regional Office, yet all harvest data were available from 1966 through 1976. However, annual harvest data for all States in the Eastern Region for years 1911 through 1965 were available in archived annual documents titled "Report of the Chief of the Forest Service" with the exception of years 1932, 1938 – 1941, and 1954, which could not be located (USFS Annual Reports). It is from these reports that all Eastern Region timber harvest data were obtained for years 1911 through 1965. To estimate harvest for years no data could be located, we identified 2 structural break points in the harvest time series and statistically confirmed trends with significantly different slopes through econometric Chow testing, resulting in subsets of harvest data spanning years 1911 – 1942 and 1942 – 1987 ($F_{df=92} = 9.13$, $p = 0.0002$; $F_{df=92} = 170.35$, $p < 0.0001$;). Linear regression was then used to estimate harvest amounts within the subsets of data for the missing years ($R^2 = 0.484, 0.886$, respectively).

All results in this report are based mainly upon fiscal year harvests. However, Eastern Region harvest data for years 1922 through 1931 were reported for calendar years only, as opposed to the most conventional reporting style of fiscal years. Fiscal year 1921 spanned July 1, 1920 to June 30, 1921 and calendar year 1922 spanned January 1 to December 31, leaving that latter half of 1921 calendar year harvest unaccounted for. This unknown harvest is not included in the analysis. Conversely, fiscal year 1932 includes the latter half of calendar year 1931, and calendar year 1931 harvest was reduced by half with the assumption that this decrease is approximately equal to half of the1932 fiscal year harvest, which includes harvest from half of calendar year 1931. Additionally, the span of fiscal years changed in 1976 to run from October 1 to the following September 30; timber harvested during the period from July 1 to September 30, 1976, known as the 'transition quarter' was removed from the analysis.

Because the model developed for this purpose requires cubic foot input metrics for harvested timber, conversion factors for specific timber products were used to convert volumes from thousand board feet (mbf) to hundred cubic feet (ccf) (Table 2). Beginning in 2001, harvested volumes have been reported in both mbf and ccf. Between 1911 and 2000 volumes were reported in mbf only. For this period annual harvest totals for Eastern Region reported in mbf were converted to ccf using a conversion factor of 1.6303 ccf per mbf (Table 2), which is the mean conversion factor obtained from harvested volumes from 2001 to 2012 when harvest volumes were reported in both mbf and ccf.

There is new evidence that ccf per mbf conversion factors have changed in recent decades. For example, Keegan et al. (2010a) have found a 16% decrease in mbf per ccf conversion in California from 1970s to 2000s. This alone would suggest conversions from mbf to ccf in earlier decades overestimate the volume harvested. On the other hand, Keegan et al. (2010b) indicate that utilization represented as cubic feet of green finished lumber per cubic foot of bole wood processed has increased during the same period by roughly the same magnitude (16% in California). This would suggest that estimates of carbon in products in use were underestimated in earlier decades. Assuming that the findings by Keegan et al. essentially cancel each other out, and considering we did not have adequate timber harvest data from all National Forests across the entire period, we chose not to incorporate this information into our calculations. In addition, analyses similar to those found in Keegan et al (2010a, 2010b) are not available for all USFS Regions. To accommodate this type of unknown variability over time, we provide an uncertainty analysis in this report, which is discussed below.

Historical timber product data

Eastern Region harvest records from 1911 through 1976 do not partition the harvest among different timber product classes; they report only total annual harvest. To estimate the proportion of total Eastern Region harvest that went into each timber product class, we applied the average annual proportion of the harvest represented by each timber product class from 1977 through 2012 to the annual harvest for each year 1911 through 1976 (Table 3).

[2] USFS 2013 (http://www.fs.fed.us/forestmanagement/products/sold-harvest/cut-sold.shtml)
[3] Many times the timber product classes recorded in cut-and-sold reports are not actually the products classes that are used after harvest. This reality, in addition to the lack data for these ratios for the entire data period, explains why we include timber and primary product ratios in our uncertainty analysis.

Table 3. The average annual proportion of 1977 through 2012 Eastern Region harvests distributed to timber product classes between 1911 and 1976 (n=36).

Product class	Mean	Std. Error
Pulpwood, hardwood	0.42	0.015
Pulpwood, softwood	0.25	0.010
Sawtimber, hardwood	0.19	0.006
Sawtimber, softwood	0.09	0.004
Fuelwood, hardwood	0.02	0.002
Other	0.02	0.005

Historical primary product data

The carbon in HWP from timber products to primary products is based upon intricate disposition connections from harvested timber products to primary products to end-uses found in Smith et al. (2006). For the Eastern Region the proportion of volume in each timber product class (e.g. softwood sawlogs) allocated to primary wood products (e.g. softwood lumber, softwood plywood, etc.) are not directly described by Smith et al. Rather, Smith et al. have partitioned the current administrative boundary of the Eastern Region into 2 sub regions (Northcentral and Northeast). To estimate primary wood product allocation for the Eastern Region, we developed weighted average ratios from those found in Smith et al. (2006) using estimates of total regional roundwood supply from Adams et al. (2006). Between Smith et al. and Adams et al., each sub region and estimate year are identical.

We were also required to make simple assumptions regarding the allocation of pulplogs to primary product categories in the years prior to the emergence of oriented strandboard; production of oriented strandboard in the US began in approximately 1978. For years 1911 to 1977 we shifted the proportion of timber product allocated to oriented strandboard to wood pulp. Additionally, we are confident that due to the well established wood product industries' history in the Eastern Region, no other adjustments to primary product ratios was necessary, and that all other industries had existed in the Eastern Region since 1911. Although we made assumptions about a few primary product classes based on historical information, in general we had a strong set of historical data to use in our calculations.

Historical end use data

The historical end use data used for the Eastern Region comes from McKeever (2009 and 2011). This national data set is used for all NFS Regions for the distribution of primary products to end uses for all regions, with no regional variation. Estimates for 1950 were used for 1911 through 1949 and estimates for 2009 were used for 1950 through 2012. We acknowledge that this is not ideal, but no other data are available for these periods. The annual end use wood product estimates are periodically updated, which could allow better HWP storage and flux estimates in the future.

Uncertainty analysis

Interpretation of the results should be made in light of some constraints. Though we attempted to normalize annual harvests to the modern boundary of the Region using forest-specific harvest data, in actuality the annual harvest is from a land base that is somewhat variable over time. The USFS has commonly engaged in land exchanges, divestments and acquisitions in the Regions since their origin, which means that the geographic boundary for Regions has not been consistent. In addition, conversion factors (which depend on average log size, mill technology and efficiency, etc.), distribution of timber products to primary products, and the distribution of primary products to end uses have changed over time. Though we have used annual data whenever possible, there is some uncertainty associated with applying averages to the early years of the harvest series.

Uncertainty is quantified using the methods described in Skog (2008). We identified the most critical sources of uncertainty in our analysis (Table 4), developed probability distributions (using expected ranges) for each of four major sources of uncertainty (conversion factors, reported harvest, product distribution variables, and product decay parameters), and carried out Monte Carlo simulations to determine the collective effect of uncertainty in these variables on estimates of HWP stocks. We did not explore the contribution of each variable in a sensitivity analysis, but instead address collective uncertainty. Further investigation into the level of uncertainty of each random variable and its effect on confidence intervals could help managers determine where to focus improvements in reporting to reduce uncertainty in carbon storage and flux estimates. Across all variables, sensitivity analyses could be used to identify variables that have the greatest impact on carbon storage and flux, and compare alternative levels of those variables associated with different scenarios of forest management and HWP production, use and disposition.

Table 4. Sources of uncertainty and range of the triangular distribution for each random variable used in the Monte Carlo simulation

Source of Uncertainty	Range of distribution	Years
Reported harvest in ccf	±30%	start to 1945
	±20%	1946 to 1979
	±15%	1980 to end
Timber product ratios	±30%	start to 1945
	±20%	1946 to 1979
	±15%	1980 to end
Primary product ratios	±30%	start to 1945
	±20%	1946 to 1979
	±15%	1980 to end
Conversion factors, ccf to MgC	±5%	all years
End use product ratios	±15%	all years
Product half lives	±15%	all years
Discarded disposition ratios (paper)	±15%	all years
Discarded disposition ratios (wood)	±15%	all years
Landfill decay limits (paper)	±15%	all years
Landfill decay limits (wood)	±15%	all years
Landfill half-lives (paper)	±15%	all years
Landfill half-lives (wood)	±15%	all years
Dump half-lives (paper)	±15%	all years
Dump half-lives (wood)	±15%	all years
Recovered half-lives (paper)	±15%	all years
Recovered half-lives (wood)	±15%	all years
Burned with energy capture ratio	±15%	all years

Because we apply different distributions to different time periods for some variables, the 23 distributions cover 17 different variables. Multiple time-delineated distributions are used for reported harvest, primary products ratios, and end use ratios, with time periods separated at benchmark years related to data quality. The probability distributions of these random variables were developed based on estimates in Skog (2008) and on professional judgment, and are assumed to be triangular and symmetric. A triangular error distribution was selected because without additional empirical information, we reasonably assume the error distribution to be symmetric with greater likelihood of values being centered in between the limits of the distribution than at one or both of the limits of the distribution. In addition, we can reasonably assign values to the limits. The distributions are assumed to be independent of one another.

The effect of uncertainty in these variables on HWP carbon storage was evaluated using Monte Carlo simulation. For each simulation, a mean value and 90% confidence intervals are the results of 3,000 iterations performed to reach a stable standard deviation in the mean (Stockmann et al. 2012). In each iteration, HWP carbon stocks are calculated using values for variables drawn at random from the established distributions. Using thousands of draws, we produce a simulation mean and a distribution of values that can be used to establish the confidence intervals shown in the tables. These confidence intervals show the range of values in which 90% of all values are expected to fall.

Results for the Eastern Region

Between 1911 and 1942 the annual timber harvests in Eastern Region was below 100,000 MgC yr^{-1} and remained under 500,000 MgC yr^{-1} through 1955 (Table 5, Figure 4). Shortly after the beginning of World War II harvests began to steadily increase through the early 1970s; however, there were several periods during this timeframe with erratic harvest levels above and below the prior year harvest. Following general harvest decreases in the late 1960s through mid-1970s, annual harvest began to steadily increase again with maximum harvest occurring in 1987 at just over 1.1 million MgC. From 1984 through 1993 there were seven years with harvests in excess of 1 million MgC, For the next decade harvests rapidly declined to a low in 2008 of approximately 466,000 MgC, the lowest harvest since 1954. Since 2009, harvest levels have remained relatively steady at around 500,000 MgC yr^{-1} (Table 5, Figure 4).

Table 5. Annual timber product output in the Eastern Region for selected years using the IPCC/EPA production accounting approach. This table shows carbon removed from the ecosystem by harvesting.

Harvest year	Harvest (ccf)	Timber product output (MgC)
1920	28,341	22,732
1930	58,833	47,189
1940	93,912	75,325
1950	331,869	266,186
1960	728,543	584,352
1970	940,036	753,996
1980	922,267	763,191
1990	1,232,043	1,021,520
1995	1,077,629	889,751
2000	893,243	731,066
2005	611,830	503,869
2006	560,414	458,351
2007	550,712	449,586
2008	573,639	466,543
2009	551,022	448,150
2010	613,816	502,501
2011	609,779	500,353
2012	668,387	553,613

The cumulative carbon stored in the Eastern Region HWP began to accelerate substantially around 1940 and increased at an increasing rate until the mid-1970s, at which time the additions to carbon storage began to slow for a brief period. In the late 1970s through the 1990s, additions began to once again accelerate and in 2001 surpassed 12 million MgC. Since this time additions to carbon storage have continued to increase, but at a rather slow rate, and in 2013 carbon stored in Eastern Region HWP will be at its highest point within the analysis timeframe with storage of slightly more than 12.8 million MgC (Figure 5, Table 6, Appendix B). For reference, this is equivalent to nearly 46.2 million $MgCO_2$, the CO_2 equivalent annual emissions from nearly 9 million passenger vehicles, 107 million barrels of oil, or the CO_2 equivalent emissions from 241,000 railcars of coal. Despite a slowdown since 2002, carbon stocks in the HWP pool for the Eastern Region have since grown steadily (Figure 5, Table 6).

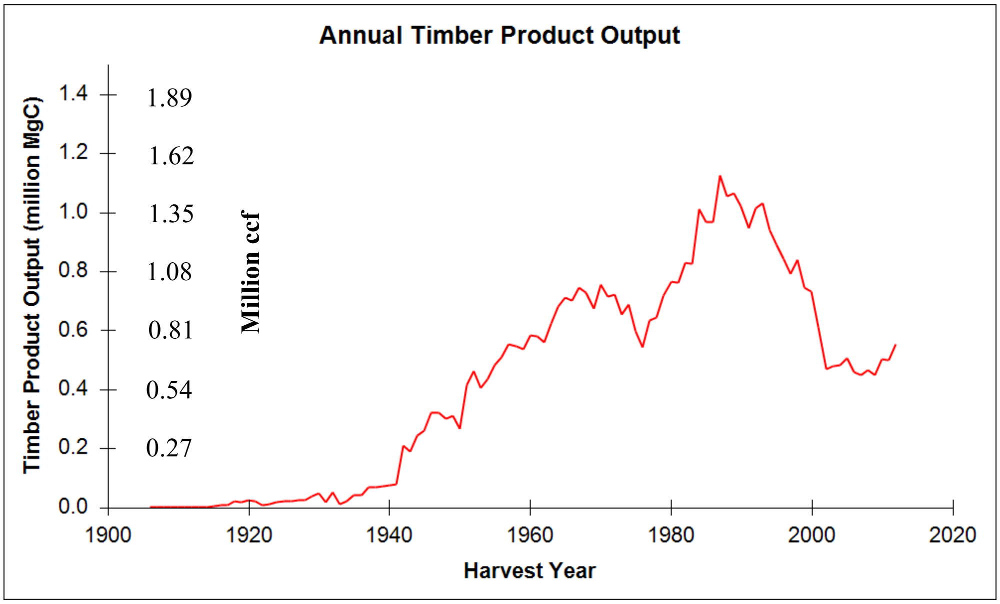

Figure 4. Annual timber product output in the Eastern Region, 1911 to 2012. Harvest estimates are based on data collected from USDA Forest Service Archives and Cut/Sold reports.

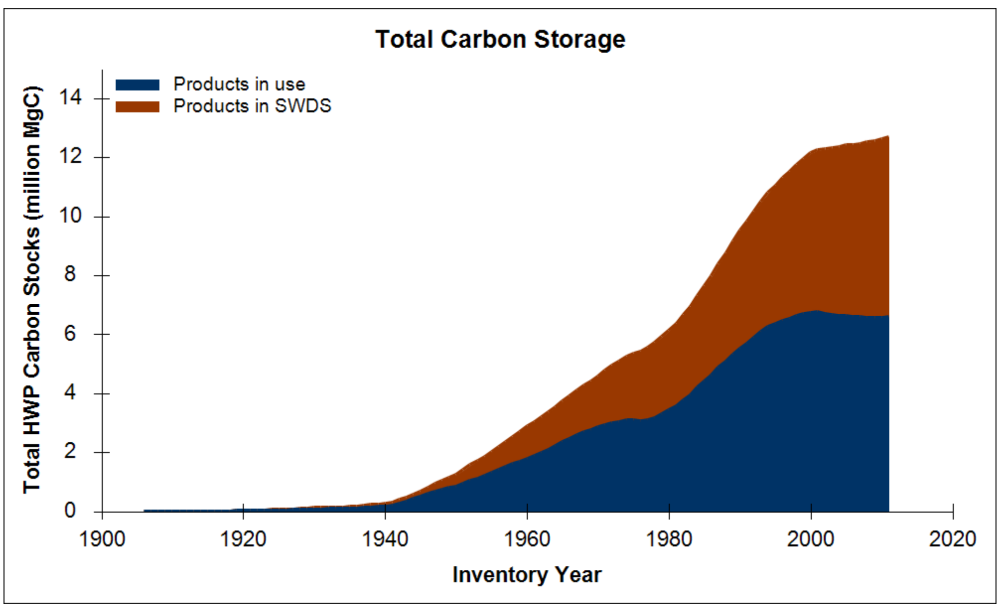

Figure 5. Cumulative total carbon stored in HWP manufactured from Eastern Region timber using the IPCC/EPA approach. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposal sites (SWDS), including landfills and dumps.

All else being equal, higher harvest levels result in more carbon removed from the ecosystem pool and added to the HWP pool (Figure 2). Figure 5 shows the cumulative carbon in both products in use and SWDS components of the HWP pool for the Region. Based on the years that match the most recent EPA report (US EPA 2012), Table 6 shows how the disposition of HWP carbon is broken into the four IPCC/EPA categories: emitted with energy capture, emitted without energy capture, products in use and products in SWDS. For each inventory year shown in the first column, the second column shows aggregate carbon emitted with energy capture (i.e. fuelwood), the third column shows aggregate carbon emitted through decay or combustion from SWDS, and the fourth and fifth columns show carbon stored in products in use and products in SWDS, respectively. The final column, the "Total in HWP pool," is the sum of products in use and carbon in SWDS. Note that the estimate for each inventory year includes the portion of HWP carbon still in use and in SWDS for all previous harvest years back to 1911 in addition to carbon harvested in the inventory year. Some of the cumulative emissions from the burned and decayed HWP (Table 6, second and third columns) are theoretically taken out of the atmosphere by regrowth on harvested sites, but this effect is accounted for in the ecosystem carbon component (NEE) of the change in carbon stock equation, not in the HWP component (H and ΔC_R).

Table 6. Cumulative disposition of Eastern Region HWP carbon for selected years using the IPCC/EPA production accounting approach. This table shows the fate of all carbon removed from the ecosystem by harvesting.

(1) Inventory year	(2) Emitted with energy capture	(3) Emitted without energy capture	(4) Products in use	(5) SWDS	(6) Total in HWP Pool[a]
			(MgC)		
1920	23,636	3,161	23,281	3,179	26,460
1930	111,089	38,145	73,145	32,786	105,931
1940	294,794	129,926	169,721	85,227	254,948
1950	1,272,193	485,488	805,410	358,248	1,163,658
1960	3,222,827	1,521,212	1,690,357	1,016,518	2,706,875
1970	6,011,389	3,537,518	2,761,882	1,659,306	4,421,188
1980	8,791,947	5,907,221	3,293,609	2,623,477	5,917,086
1990	12,754,865	7,953,853	5,320,274	3,830,807	9,151,082
1995	14,792,295	9,248,683	6,250,650	4,547,985	10,798,634
2000	16,468,261	10,548,822	6,700,747	5,257,374	11,958,121
2005	17,600,706	11,851,900	6,652,950	5,705,198	12,358,148
2006	17,806,845	12,102,779	6,647,540	5,766,516	12,414,056
2007	17,999,648	12,347,940	6,618,277	5,825,147	12,443,424
2008	18,188,495	12,587,050	6,590,769	5,881,790	12,472,560
2009	18,383,862	12,820,044	6,578,829	5,937,629	12,516,458
2010	18,573,127	13,047,175	6,558,802	5,993,430	12,552,233
2011	18,782,998	13,269,207	6,575,099	6,049,659	12,624,758
2012	18,989,735	13,486,694	6,593,725	6,107,881	12,701,606
2013	19,212,512	13,700,476	6,649,502	6,168,405	12,817,906

[a] Sum of Products in use and SWDS.

Figure 6 and Table 7 present the trend in terms of net annual change in HWP carbon stocks. Negative net annual change in HWP carbon stocks values means that total carbon stored in the HWP pool in the inventory year is lower than in the previous year. In other words, a decline in the HWP pool results in a transition from a positive net annual change in carbon stocks to a negative net annual change in carbon stocks. Beginning in the mid 1940s additions to carbon stocks in HWP were growing by over 100,000 MgC yr^{-1} and increased steadily before stabilizing somewhat in the late 1950s through early 1970s with additions of slightly less than 200,000 MgC yr^{-1}. Additions to carbon stocks began to decrease through the late 1970s, which was then followed by a steady increase with peak stock growth in 1988 with the addition of slightly more than 410,000 MgC. This was followed by a steep decline of additions to the HWP pool through the 1990s and early 2000s. In 2003, the net change began to stabilize and has shown slight overall increases.

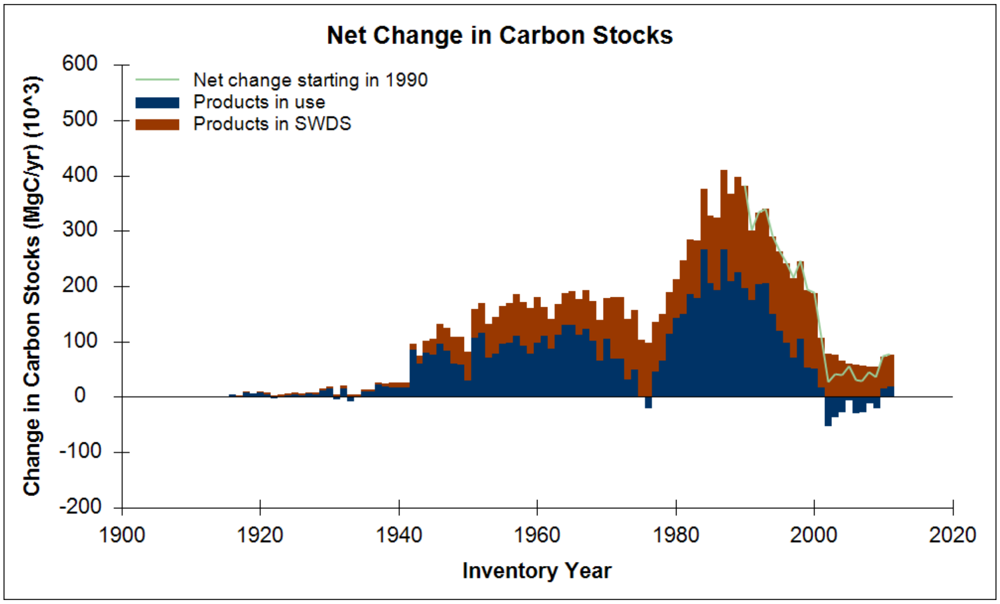

Figure 6. The net change in carbon stocks in HWP from the previous year using the IPCC/EPA production accounting approach. The net stock change is the sum of net change for SWDS and products in use. The total net change trend line shows a transition from net additions to carbon stocks in HWP to a period of net loss in HWP.

Table 7. Annual net change in HWP carbon stocks for selected years for harvests.

Inventory Year	Stock change[a] (MgC yr^{-1})
1920	7,453
1930	15,907
1940	26,139
1950	109,942
1960	161,341
1970	139,376
1980	189,756
1990	397,911
1995	290,631
2000	192,926
2005	38,744
2006	55,908
2007	29,368
2008	29,135
2009	43,898
2010	35,775
2011	72,525
2012	76,848
2013	116,301

[a]Net annual change in C in products in use and SWDS.

Unlike many other USFS Regions, emissions from Eastern Region HWP carbon stocks have never exceeded additions. Since 1988 the most recent year with the least additions to the Eastern Region HWP carbon pool was 2003, when only 26,000 MgC were added; however, additions to the HWP through new harvest have always been greater than emissions from the HWP pool. Recall that these estimates relate only to HWP and do not quantify carbon fluxes in the ecosystem pool.

To quantify uncertainty, confidence intervals were estimated for HWP stock estimates using Monte Carlo simulation, representing 18 random variable distributions, with distributions determined from publications and expert opinion. Table 8 shows the resulting confidence intervals for the IPCC/EPA estimates for selected years. For 2013, the year of peak carbon stocks in Table 8, the 90% confidence interval ranges from 12,805,560 MgC to 12,817,906 MgC, with a mean value of 12,811,733 MgC. This is equivalent to a ±0.05% difference from the mean.

Table 8. Confidence intervals for cumulative carbon in HWP for selected years for harvests beginning in 1920 using the IPCC/EPA production accounting approach. Means and confidence intervals were calculated using Monte Carlo simulation (3,000 iterations).

Inventory year	Simulation Mean (MgC)	90% Confidence interval Lower limit (MgC)	Upper limit (MgC)
1920	26,420	26,367	26,473
1930	105,881	105,748	106,013
1940	254,752	254,453	255,052
1950	1,166,344	1,165,154	1,167,533
1960	2,708,930	2,706,784	2,711,075
1970	4,421,108	4,417,875	4,424,342
1980	5,916,755	5,912,763	5,920,747
1990	9,150,095	9,145,089	9,155,100
1995	10,793,951	10,788,462	10,799,440
2000	11,952,566	11,946,720	11,958,412
2005	12,351,686	12,345,737	12,357,636
2006	12,407,733	12,401,769	12,413,697
2007	12,437,673	12,431,699	12,443,647
2008	12,466,839	12,460,846	12,472,833
2009	12,510,682	12,504,671	12,516,693
2010	12,546,363	12,540,324	12,552,402
2011	12,618,628	12,612,566	12,624,690
2012	12,695,850	12,689,757	12,701,942
2013	12,811,733	12,805,560	12,817,906

Discussion of Regional-level Estimates

National context

Although these results rely on numerous calculations, the time series of annual harvest volume (Figure 4) is at the root of the trends in carbon stocks and flux for the regional HWP pool. Several recent publications help put these HWP carbon estimates in the context of the total forest carbon, including both ecosystem carbon and HWP carbon (Heath et al. 2011, US EPA 2012). By dividing the 2006 HWP stock estimate of 12.4 teragrams of carbon (TgC) presented in Table 6 by the sum of this stock estimate and Heath et al.'s (2011) estimated 2006[4] Eastern Region

[4] Mean measurement year reported as 2005.6.

ecosystem carbon stock of 1,073 TgC, we estimate that the Eastern Region HWP carbon stocks represent roughly 1.1% of total forest carbon storage associated with National Forests in the Eastern Region as of 2006. At the national level, based on the EPA's total US HWP 2006 stock estimate of 2,383 TgC (US EPA 2012), the Eastern Region HWP carbon stocks represented less than 1% of total US HWP carbon stocks.

Estimates of forest ecosystem flux in the western US exist (Healey et al. 2009, Heath et al. 2011, Van Deusen and Heath 2007) and others in development. However, long-term data collection requirements will delay reporting until the USFS Forest Inventory and Analysis Program completes its second cycle of plot measurements. However, our calculations of HWP carbon flux will allow the Eastern Region to reasonably account for carbon that was harvested from National Forests over the study period. Ideally, when changes in forest ecosystem carbon are quantified in subsequent research they can be linked with the HWP estimates described here.

Applications of this approach by forest managers

The methods presented here for estimating the HWP carbon pool will allow resource managers and the public to develop a more complete understanding of the dynamics of HWP as a component of total forest carbon pool, and may allow the evaluation of the effect of alternative harvesting intensities on carbon stocks and fluxes. Furthermore, a benefit may be realized by evaluating the feasibility, utility, uncertainty, and limitations of the metrics and estimation methods that could be used to meet carbon monitoring objectives.

The IPCC/EPA approach requires harvest information for many prior years to make an estimate of net change to carbon stocks each inventory year over time. We recommend that all applications of the IPCC/EPA approach consider the quality of the data and adjust their uncertainty analysis accordingly, particularly with regards to the distributions of random variables (e.g., Table 4). However, though carbon of older vintages may be associated with higher uncertainty, it is also likely to have a smaller impact on current stocks and fluxes than more recent harvests. For example, the importance of the early harvests for the Northern Region – which spans northern Idaho, Montana, North Dakota, South Dakota, and eastern Washington – was estimated by Stockmann et al. (2012) by quantifying the portion of the current HWP pool that is attributable to carbon harvested prior to 1950. In 1950 the Northern Region HWP carbon pool was 4.5 million MgC. By inventory year 2010, only 1.7 million MgC of the carbon harvested before 1950 remained in products in use and SWDS, which accounted for 6.6% of the total stocks of 25.8 million MgC in 2010. Although we do not provide a similar estimate for the Eastern Region, we believe the same trend is likely to hold for most regions. This small contribution to current stocks is a result of two factors. First, there was greater harvesting activity for the period after than before 1950. Second, following the passage of the Resource Conservation and Recovery Act of 1976 (RCRA, 42 USC 6901) and after a short lag, a much larger portion of discarded HWP goes into modern landfills where it is subject to lower rates of decay than in aerobic dumps or disposal by open burning, which were the dominant disposal methods prior to RCRA.

Obtaining historical information may present a challenge for some National Forests. It may be particularly difficult to reconstruct harvest data prior to the mid-1940s, though regression of trends after the period might be appropriate for extrapolation to earlier periods. Alternatively, regions could base their carbon accounting on national level parameters, making the assumption that national-level numbers are adequate for regional and sub-regional analysis. If national level values represent the best available data, the IPCC/EPA method requires only harvest volume information from the user. Many regional and forest type-specific default dynamics and decay functions are supplied by national level efforts (Skog 2008, Smith et al. 2006). The simplicity associated with using national data in calculations may make the system functional and effective in meeting monitoring needs for forest managers both within and outside the USFS, regardless of data quality. If superior information exists for smaller scale units, it may be possible to substitute these ratios and conversion factors into the modeling effort. However, one needs to be mindful that the results of tailored analyses might not match up with results across the country and NFS. This could be a source of interesting future research.

We successfully applied the methods described by Skog (2008) to estimate the uncertainty associated with our HWP carbon stock estimates (Table 8). However, it is unclear how the magnitude of this uncertainty would change, if at all, if the analysis were done on smaller management units (e.g. the individual National Forest level). The change in uncertainty would, in large part, depend on assumptions made about the distributions of random variables used in the analysis. In some cases, a regional analysis may be sufficient to inform forest-level land management planning, forest management practices, and planning of long-term (programmatic) timber harvest levels and associated effects on carbon flux. A detailed sub-regional analysis may be needed where there are significant within-region differences in ecosystems and disturbance processes and harvest levels.

Conclusions

HWP is an important carbon pool that should be considered in decision making associated with carbon monitoring and climate change adaptation and mitigation. However, as $\Delta S = (NEE - H) + (\Delta C_R)$ shows, total forest carbon is a function of both HWP and ecosystem carbon, which may have increased over the study period. This report fits into a larger effort to address this entire system, the Forest Carbon Management Framework, which is currently under development. Together with accounting and modeling methods that quantify ecosystem forest carbon, the approaches used in this study provide a powerful tool to monitor carbon stocks, stock change, as well as the ability to assess the possible outcomes of management actions intended to reduce the vulnerability of forest resources to climate change.

Though our analysis is at the Regional level, we provide a framework by which the IPCC/EPA method can be applied broadly at other administrative units and forests to estimate harvest (H) and the resulting change in HWP carbon stocks for the region (ΔC_R). We estimated ΔC_R each year by summing our estimates for the change of carbon stored in products in use from wood harvested in the region ($\Delta C_{IU\ R}$) and the change of carbon stored in solid waste disposal systems from wood harvested in the region ($\Delta C_{SWDS\ R}$). Although we did not have access to detailed recent information about wood harvest in agency cut-and-sold reports, we were fortunate to have archived historic harvest volume records. As expected, records for the partitioning of the harvest to timber and primary product classes improved markedly as our records approached the present time. Although we applied timber product distributions, primary product distributions, and end use product distributions from the more recent years to earlier years of harvest and we made adjustments to primary product distributions to reflect the manufacturing onset for several primary product classes based on historical information, in general we had a strong set of historical data to use in our calculations.

The Eastern Region HWP pool has always been in a period of positive net annual stock because additions of carbon to the HWP pool through harvest exceeds the decay of products harvested between 1911 and 2012 (Tables 6 and 7). The IPCC/EPA production accounting approach is data intensive because it includes past harvest and product disposition data for each inventory year, but it provides estimates of total stocks and stock change making it congruent with national accounting and reporting protocols.

The IPCC/EPA approach could be used to predict changes to the HWP component of the forest carbon pool resulting from planned or potential change in the amount of wood harvested. Quantifying uncertainty is an important component regardless of the analytical approach used because it quantifies the confidence we have in estimates of carbon stocks. We believe further research is necessary to help policy makers and managers better understand the implications of alternative forest management strategies on forest carbon stocks and stock change. An integrated approach might include consequential LCA that evaluates changes in harvest activity on carbon emissions including all sources of emissions and product substitutions.

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Appendix A

Distribution of timber products to primary wood products for regions of the US (Smith et al. 2006).

Table D6.—Fraction of each classification of industrial roundwood according to category as allocated to primary wood products (based on data from 2002)[a]

Region	Category[b] SW/HW	Category[b] SL/PW	Softwood lumber	Hardwood lumber	Softwood plywood	Hardwood plywood[c]	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp	Fuel and other emissions
Northeast	SW	SL	0.391	0	0.004	0	0	0.020	0.083	0.072	0.431
		PW	0	0	0	0	0.010	0.016	0	0.487	0.487
	HW	SL	0	0.492	0	0.005	0	0.022	0.038	0.058	0.386
		PW	0	0	0	0	0.293	0.007	0	0.350	0.350
North Central	SW	SL	0.378	0	0	0	0	0.049	0.120	0.084	0.370
		PW	0	0	0	0	0.020	0.009	0	0.486	0.486
	HW	SL	0	0.458	0	0.006	0	0.013	0.044	0.064	0.415
		PW	0	0	0	0	0.361	0.009	0	0.315	0.315
Pacific Northwest, East	SW	All	0.422	0	0.069	0	0	0.001	0.001	0.144	0.363
Pacific Northwest, West	SW	SL	0.455	0	0.089	0	0	0.009	0.073	0.114	0.260
		PW	0	0	0	0	0	0	0	0.500	0.500
	HW	All	0	0.160	0	0.140	0	0.002	0	0.229	0.469
Pacific Southwest	SW	All	0.454	0	0	0	0	0.040	0.036	0.145	0.325
Rocky Mountain	SW	All	0.402	0	0.054	0	0	0.033	0.062	0.153	0.296
Southeast	SW	SL	0.350	0	0.076	0	0	0.027	0.054	0.129	0.364
		PW	0	0	0	0	0.103	0.004	0	0.447	0.447
	HW	SL	0	0.455	0	0.006	0	0.049	0.012	0.087	0.391
		PW	0	0	0	0	0.180	0.002	0	0.409	0.409
South Central	SW	SL	0.324	0	0.130	0	0	0.019	0.023	0.133	0.371
		PW	0	0	0	0	0.135	0.006	0	0.430	0.430
	HW	SL	0	0.434	0	0.023	0	0.025	0.003	0.102	0.413
		PW	0	0	0	0	0.160	0.001	0	0.419	0.419
West[d]	HW	All	0	0.039	0	0.301	0	0.015	0.066	0.147	0.432

[a]Data based on Adams and others (2006).
[b]SW/HW=Softwood/Hardwood, SL/PW=Saw log/Pulpwood. Saw log includes veneer logs.
[c]Hardwood plywood fractions are pooled with nonstructural panels when allocating roundwood to the primary products listed in Tables 8 and 9.
[d]West includes hardwoods in Pacific Northwest, East; Pacific Southwest; Rocky Mountain, North; and Rocky Mountain, South.

Appendix B

Disposition of HWP carbon for all years. This table shows the fate of all carbon removed from the ecosystem by harvesting.

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1912	415	13	520	-	520
1913	846	55	969	30	999
1914	1,016	118	1,018	118	1,136
1915	1,356	195	1,278	230	1,508
1916	2,482	317	2,485	346	2,832
1917	6,022	589	6,515	535	7,051
1918	8,412	1,061	8,420	1,017	9,437
1919	16,498	1,860	17,176	1,830	19,007
1920	23,636	3,161	23,281	3,179	26,460
1921	33,260	4,985	31,561	5,323	36,884
1922	41,571	7,362	36,915	8,104	45,019
1923	44,677	10,050	35,030	11,423	46,453
1924	49,524	12,887	35,892	14,593	50,485
1925	56,352	15,985	39,288	17,281	56,569
1926	65,406	19,473	45,074	19,882	64,956
1927	73,502	23,386	48,853	22,718	71,572
1928	83,941	27,737	55,144	25,810	80,953
1929	94,632	32,602	60,896	29,128	90,023
1930	111,089	38,145	73,145	32,786	105,931
1931	131,068	44,663	87,969	37,076	125,045
1932	137,682	51,824	83,835	42,519	126,354
1933	158,991	59,549	99,292	48,058	147,350
1934	163,008	67,812	90,776	53,481	144,257
1935	171,216	76,057	89,473	58,786	148,259
1936	188,255	84,707	99,831	62,724	162,555
1937	206,163	94,098	109,805	66,635	176,439
1938	234,979	104,576	132,094	71,309	203,403
1939	264,225	116,521	151,476	77,332	228,809
1940	294,794	129,926	169,721	85,227	254,948
1941	326,685	145,074	187,133	94,490	281,623
1942	359,900	161,687	203,946	104,618	308,565
1943	449,057	181,560	288,776	115,618	404,394
1944	529,590	206,443	348,942	131,204	480,145
1945	632,830	236,482	428,599	154,107	582,706
1946	743,344	272,528	505,369	182,843	688,212

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1947	878,678	315,351	602,216	217,876	820,092
1948	1,014,657	365,570	685,769	259,373	945,142
1949	1,141,443	422,492	746,554	307,162	1,053,716
1950	1,272,193	485,488	805,410	358,248	1,163,658
1951	1,384,893	553,750	835,263	410,524	1,245,787
1952	1,560,369	628,027	942,583	462,290	1,404,872
1953	1,755,467	711,074	1,059,644	516,001	1,575,645
1954	1,927,058	802,368	1,131,273	577,376	1,708,649
1955	2,110,565	900,865	1,210,366	643,570	1,853,936
1956	2,315,231	1,007,267	1,307,378	711,267	2,018,644
1957	2,530,474	1,122,241	1,406,223	781,786	2,188,009
1958	2,764,854	1,246,326	1,517,575	856,071	2,373,646
1959	2,995,561	1,379,595	1,610,994	934,539	2,545,534
1960	3,222,827	1,521,212	1,690,357	1,016,518	2,706,875
1961	3,470,235	1,673,555	1,787,929	1,099,489	2,887,418
1962	3,716,276	1,839,204	1,898,993	1,150,955	3,049,948
1963	3,953,043	2,015,863	1,985,674	1,205,347	3,191,021
1964	4,216,994	2,202,477	2,097,966	1,260,885	3,358,850
1965	4,505,452	2,399,631	2,228,244	1,317,908	3,546,153
1966	4,805,772	2,607,646	2,358,538	1,378,760	3,737,299
1967	5,103,090	2,825,947	2,470,997	1,444,235	3,915,232
1968	5,418,292	3,054,183	2,594,985	1,513,158	4,108,142
1969	5,726,010	3,291,988	2,696,753	1,585,059	4,281,811
1970	6,011,389	3,537,518	2,761,882	1,659,306	4,421,188
1971	6,330,618	3,756,689	2,866,565	1,732,900	4,599,465
1972	6,632,759	3,982,059	2,935,441	1,844,365	4,779,805
1973	6,937,638	4,212,989	3,004,712	1,956,421	4,961,132
1974	7,215,027	4,448,631	3,035,854	2,066,941	5,102,795
1975	7,506,035	4,688,253	3,086,463	2,174,003	5,260,467
1976	7,758,273	4,931,036	3,086,457	2,276,922	5,363,380
1977	7,988,326	5,175,049	3,065,439	2,374,867	5,440,306
1978	8,243,976	5,420,292	3,112,135	2,463,930	5,576,065
1979	8,503,434	5,664,221	3,178,752	2,548,578	5,727,330
1980	8,791,947	5,907,221	3,293,609	2,623,477	5,917,086
1981	9,100,365	6,112,943	3,436,547	2,693,653	6,130,200
1982	9,410,972	6,317,749	3,586,110	2,790,613	6,376,723
1983	9,750,461	6,521,390	3,771,724	2,890,275	6,661,999
1984	10,086,353	6,723,774	3,950,823	2,994,845	6,945,668

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1985	10,507,880	6,925,535	4,217,206	3,105,301	7,322,507
1986	10,936,853	7,126,972	4,423,061	3,227,018	7,650,079
1987	11,361,780	7,329,417	4,617,148	3,357,501	7,974,649
1988	11,852,887	7,534,151	4,884,798	3,500,521	8,385,319
1989	12,315,021	7,742,009	5,094,222	3,658,949	8,753,170
1990	12,754,865	7,953,853	5,320,274	3,830,807	9,151,082
1991	13,175,214	8,205,745	5,517,667	4,015,751	9,533,418
1992	13,563,153	8,462,286	5,692,287	4,142,251	9,834,538
1993	13,983,598	8,722,087	5,895,742	4,272,371	10,168,113
1994	14,406,709	8,984,668	6,100,954	4,407,049	10,508,003
1995	14,792,295	9,248,683	6,250,650	4,547,985	10,798,634
1996	15,157,096	9,512,702	6,370,834	4,691,827	11,062,662
1997	15,498,920	9,775,521	6,469,374	4,835,779	11,305,153
1998	15,823,446	10,035,950	6,541,465	4,978,397	11,519,862
1999	16,164,501	10,293,986	6,647,122	5,118,074	11,765,195
2000	16,468,261	10,548,822	6,700,747	5,257,374	11,958,121
2001	16,766,951	10,810,829	6,751,798	5,394,074	12,145,872
2002	17,014,380	11,075,233	6,769,089	5,483,763	12,252,851
2003	17,206,092	11,336,280	6,716,667	5,562,351	12,279,018
2004	17,400,162	11,596,202	6,680,819	5,638,585	12,319,404
2005	17,600,706	11,851,900	6,652,950	5,705,198	12,358,148
2006	17,806,845	12,102,779	6,647,540	5,766,516	12,414,056
2007	17,999,648	12,347,940	6,618,277	5,825,147	12,443,424
2008	18,188,495	12,587,050	6,590,769	5,881,790	12,472,560
2009	18,383,862	12,820,044	6,578,829	5,937,629	12,516,458
2010	18,573,127	13,047,175	6,558,802	5,993,430	12,552,233
2011	18,782,998	13,269,207	6,575,099	6,049,659	12,624,758
2012	18,989,735	13,486,694	6,593,725	6,107,881	12,701,606
2013	19,212,512	13,700,476	6,649,502	6,168,405	12,817,906